Inclusive Jet Production in Run II at CDF.

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Outline

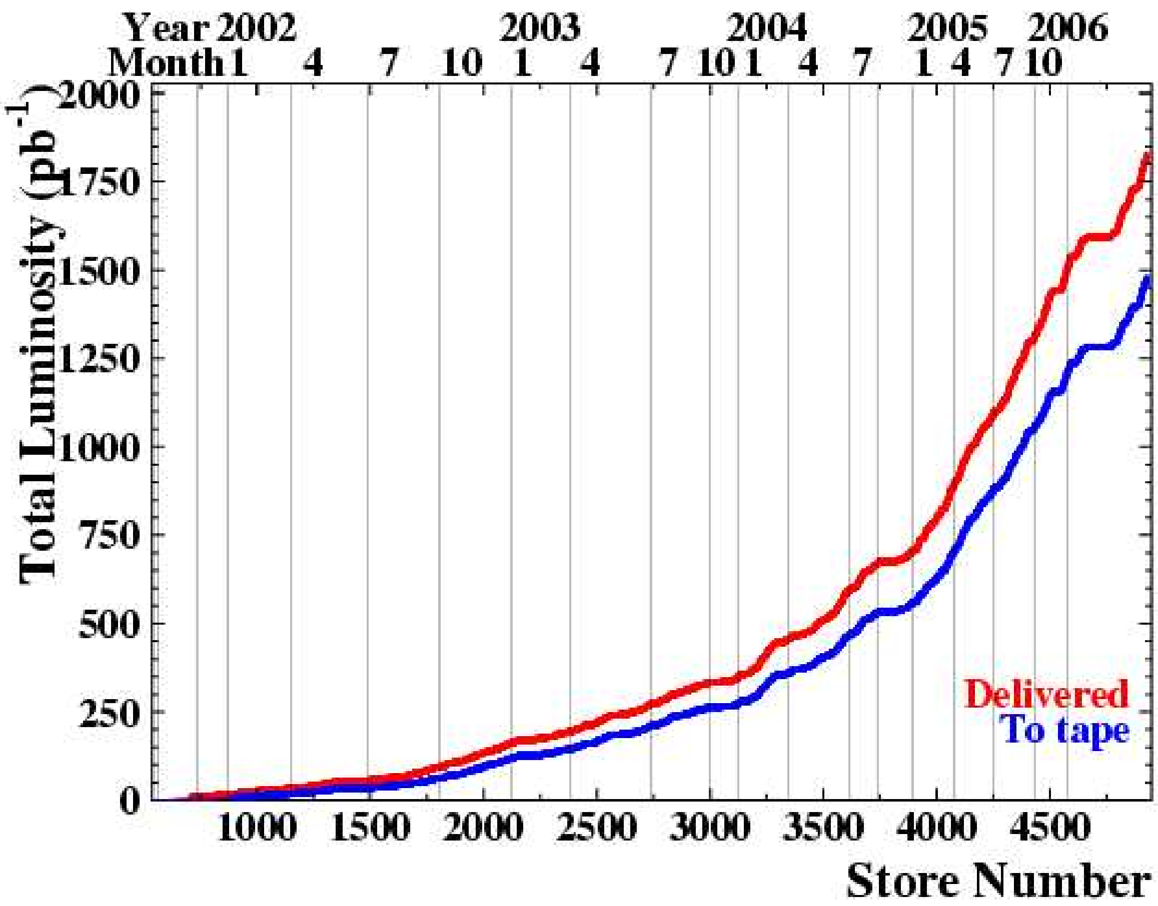
- FNAL, the Tevatron, and CDF
- Motivation
- Jet production at the Tevatron
- Jet algorithms
- Determination of the jet energy scale
- Jet corrections
- Recent inclusive jet cross section results
- Summary of other research experience

FNAL: Fermi National Accelerator Lab

The Tevatron currently provides the highest energy proton-antiproton collisions in the world.

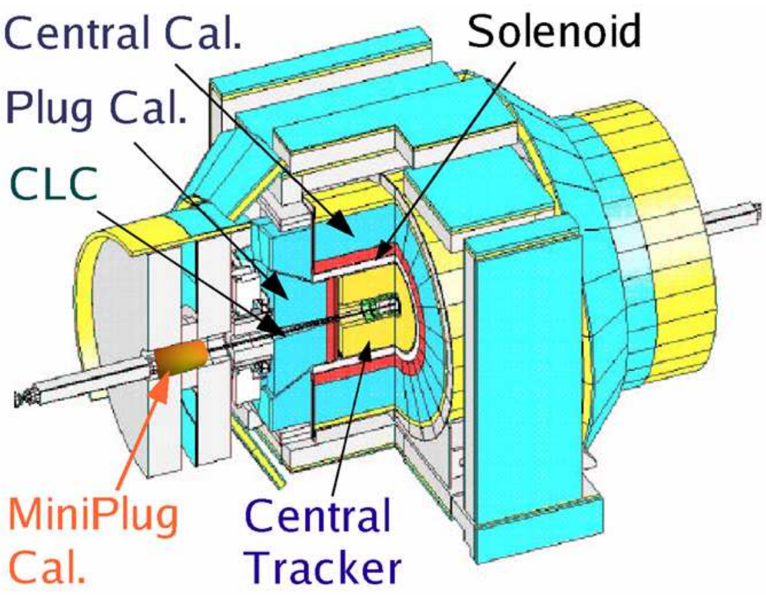
$$\sqrt{s} = 1.96 \text{ TeV}$$

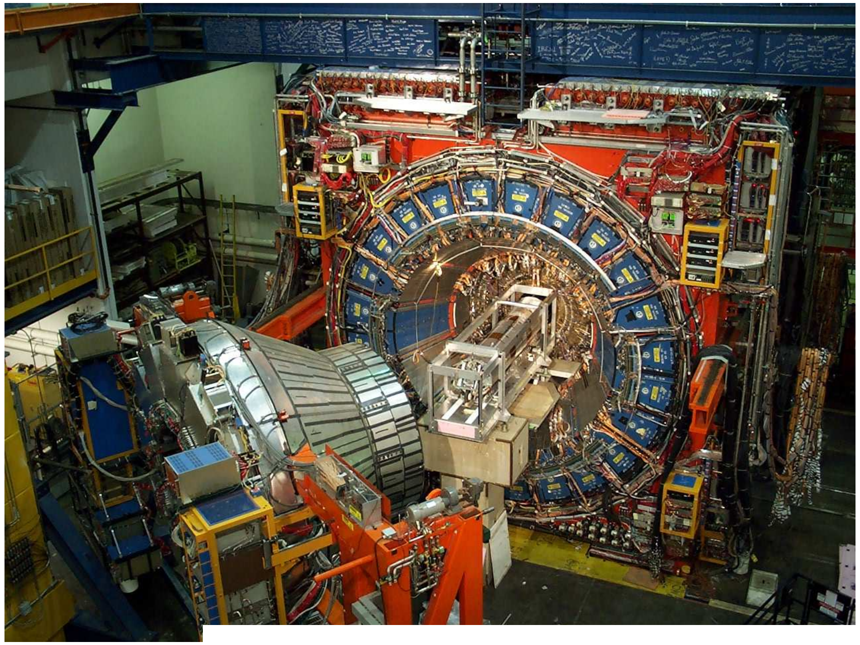
The Tevatron at FNAL



- The Tevatron at FNAL provides proton-antiproton collisions with a center of mass energy of 1.96 TeV.
- Approximately $1.5 fb^{-1}$ of integrated luminosity has been recorded to tape at CDF (More than $10 \times$ the Run I integrated luminosity).

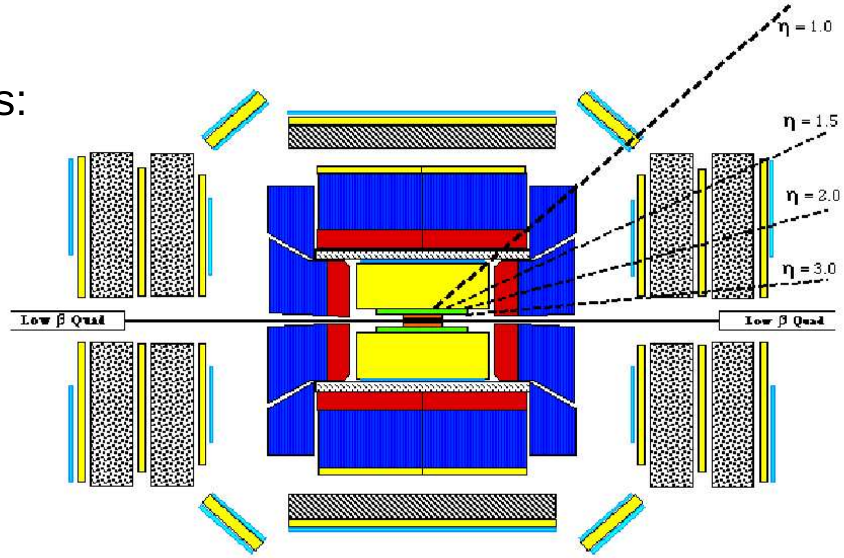
The CDF Experiment





Jet measurements rely on several detector components:

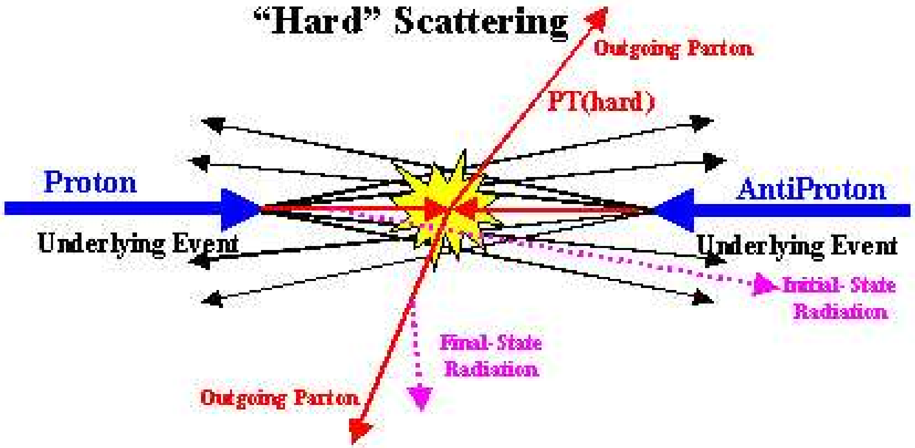
- CLC: luminosity measurement
- COT: tracking for vertex reconstruction
- Electromagnetic Calorimeters: Jets, $e^{\pm}$, and γ
- Hadronic Calorimeters: Jets



Jet Production at the Tevatron

∗ Components of a hadron collider event:

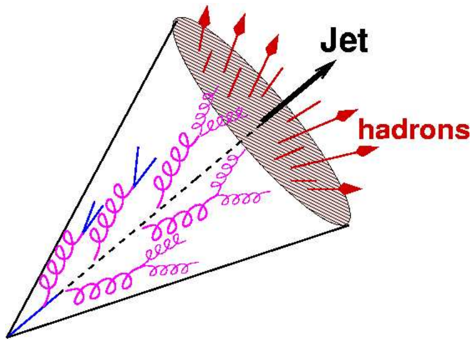
- 2⟶2 'hard' scattering
  - Described by perturbative QCD.
  - Dominated by dijet events.
- Initial and final state radiation (ISR and FSR)
- Underlying event (UE)
  - Beam-beam remnants
  - MPI (multiple parton interactions)



∗ Colored partons hadronize into color neutral hadrons.

∗ Particles from ISR, FSR, UE, and the 'hard' scattering are indistinguishable in the detector.

∗ Jet clustering algorithms combine particle energies from all of the components of the event to form jets.



Motivation: Inclusive Jet Cross Section

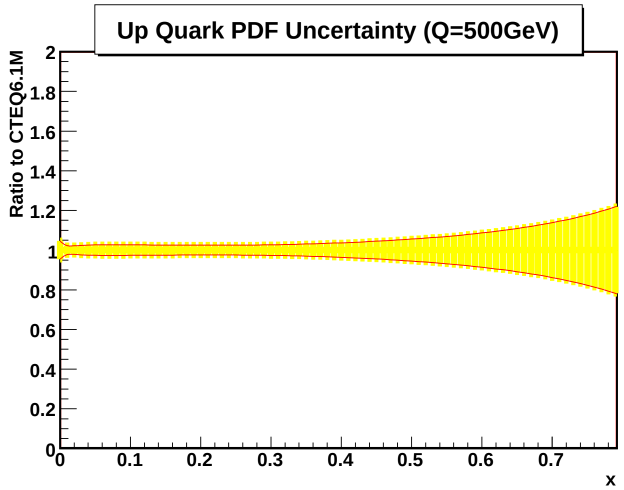
- Theoretically simple $\longrightarrow$ fundamental test of pQCD.
- Measurement over 8 orders of magnitude

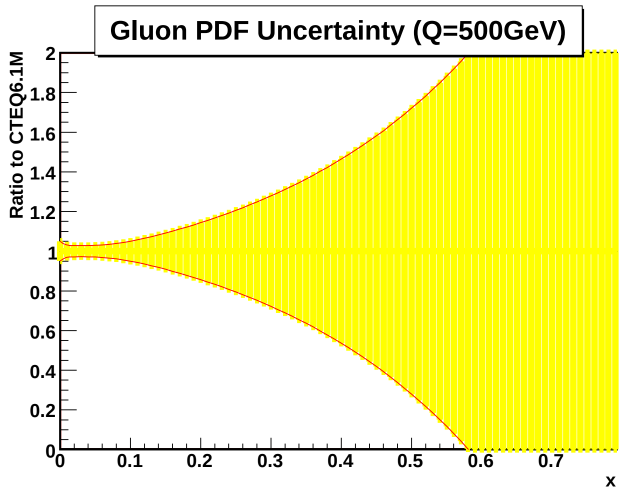
in cross section.

- Wide P_T range $\longrightarrow$ probes running of α_s.
- Probe distance scale of order $10^{-19}m$.
- Sensitive to new physics $\longrightarrow$ quark substructure.
- Probe large x $\longrightarrow$ constrain gluon PDFs.
- Benefit of including the forward region:

$\longrightarrow$ Less sensitive to new physics.

$\longrightarrow$ Provides extra constraints on standard model (PDFs).





Jet Finding Algorithms

Need to define jet clustering algorithms that 'map' the final states onto jets.

(from QCD predictions and from data)

- Additional desired properties
  - Same algorithm at parton, hadron, and detector level
  - Infrared and collinear safe
  - Fully specified and easy to use
  - Independent of detector geometry/granularity
  - ...
- 2 types of algorithms employed at CDF
  - Cone algorithm: group particles based on separation in $Y - \phi$ space. (Midpoint algorithm)
  - K_T algorithm: group particles based on their relative transverse momenta (and separation in $Y - \phi$ space).

NOTE: Different algorithms produce different observable. Midpoint and K_T are not expected to produce the same result.

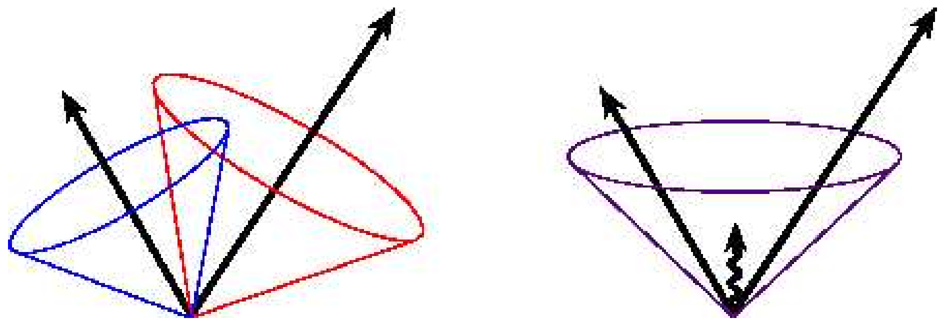
The Midpoint Jet Clustering Algorithm

A basic cone algorithm was used in Run I (JetClu):

- Start with *seed* towers.

  (calorimeter towers with energy above given threshold)

- Cluster towers within the cone radius.
- Iterate to find stable cone.
- Sensitive to 'soft' radiation.



Midpoint algorithm replaced JetClu as the cone algorithm in CDF for Run II

- Add extra *seeds* at the midpoint between all stable cones.
- Check for an additional stable cone at the midpoint between all stable cones.
- Less sensitive to 'soft' radiation.

The K_T Algorithm

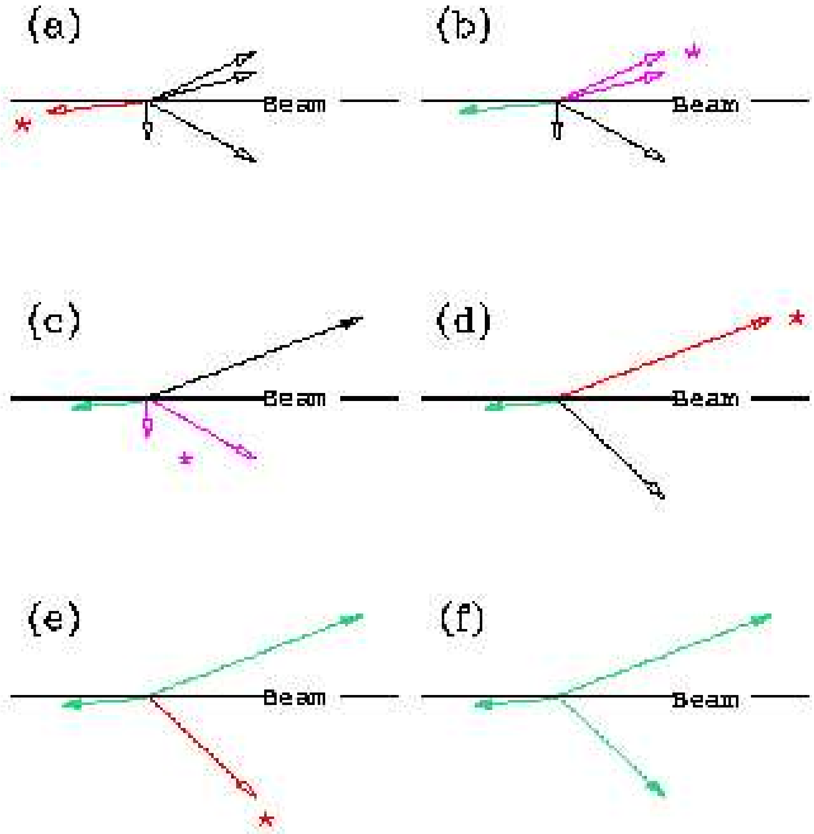
1) Construct for each particle and pair of particles:

$d_{ij} \equiv min(P^2_{T\,i}, P^2_{T\,j}) \times \frac{\Delta R^2}{D^2}$ and $d_i \equiv P^2_{T\,i}$

2) Start with $min(d_{ij}, d_i)$:

- If a d_i is the smallest, promote it to a jet.
- If a d_{ij} is the smallest, combine particles.

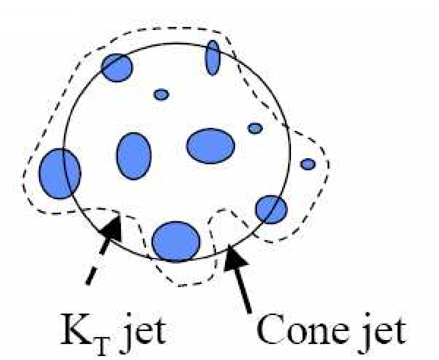
3) Iterate until all particles are in a jet.



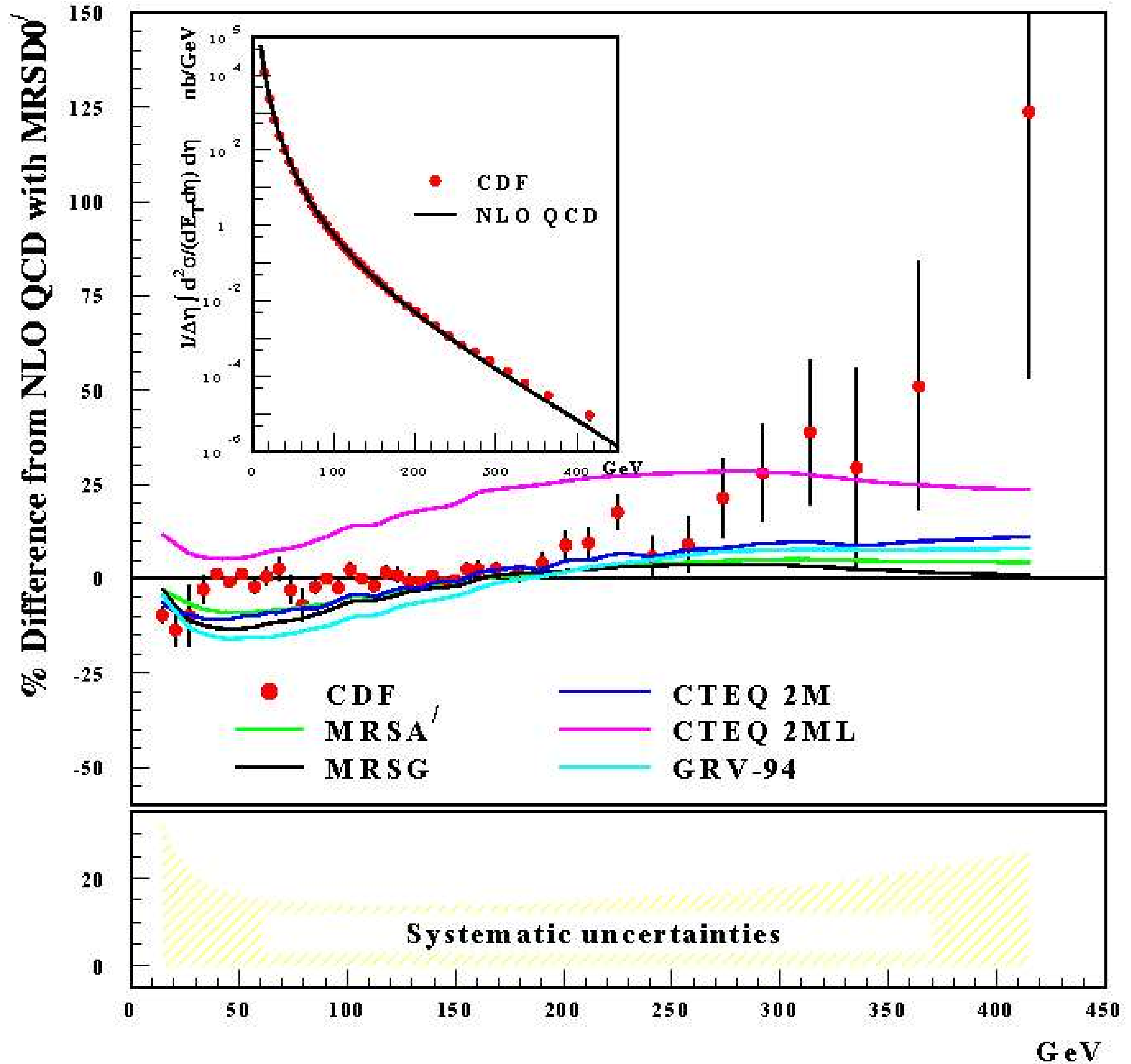
K_T Algorithm is theoretically preferred.

- Infrared/collinear safe to all orders in pQCD.

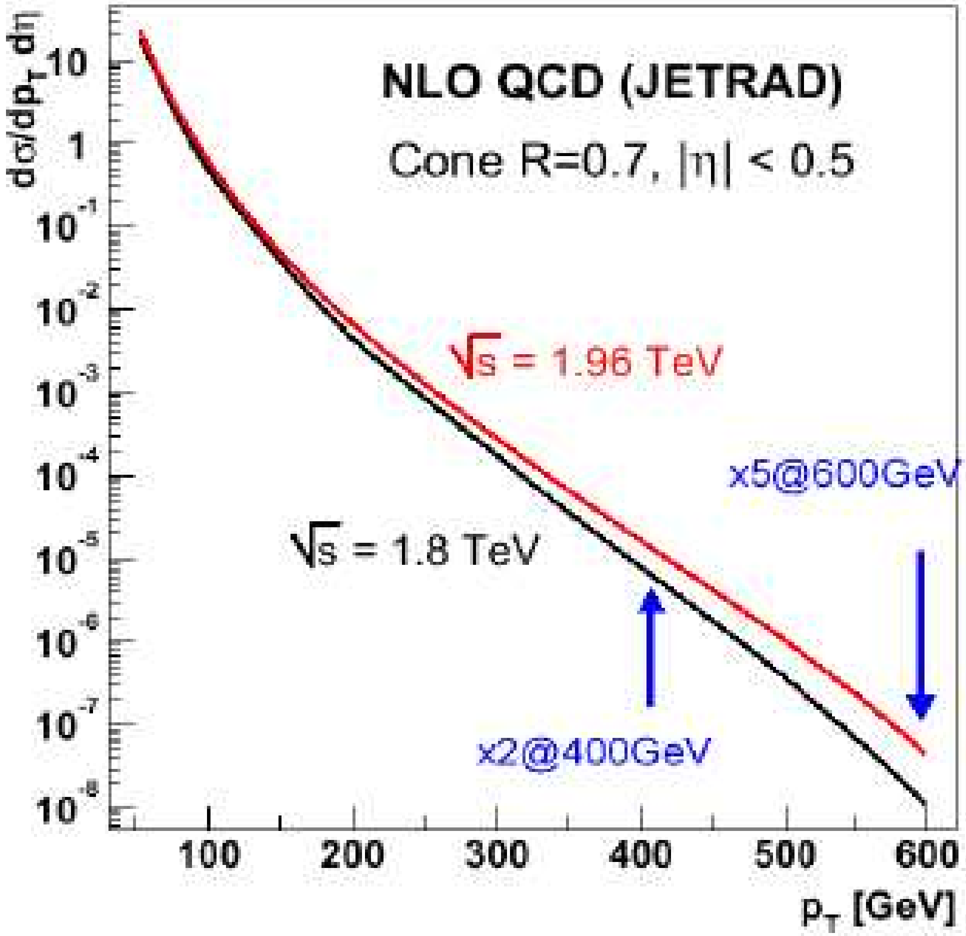
K_T has been used successfully at e+e- and ep colliders, but is relatively new to the hadron-hadron collider environment.



CDF Run 1a Inclusive Cross Section (1996)



Run I and Run II predictions



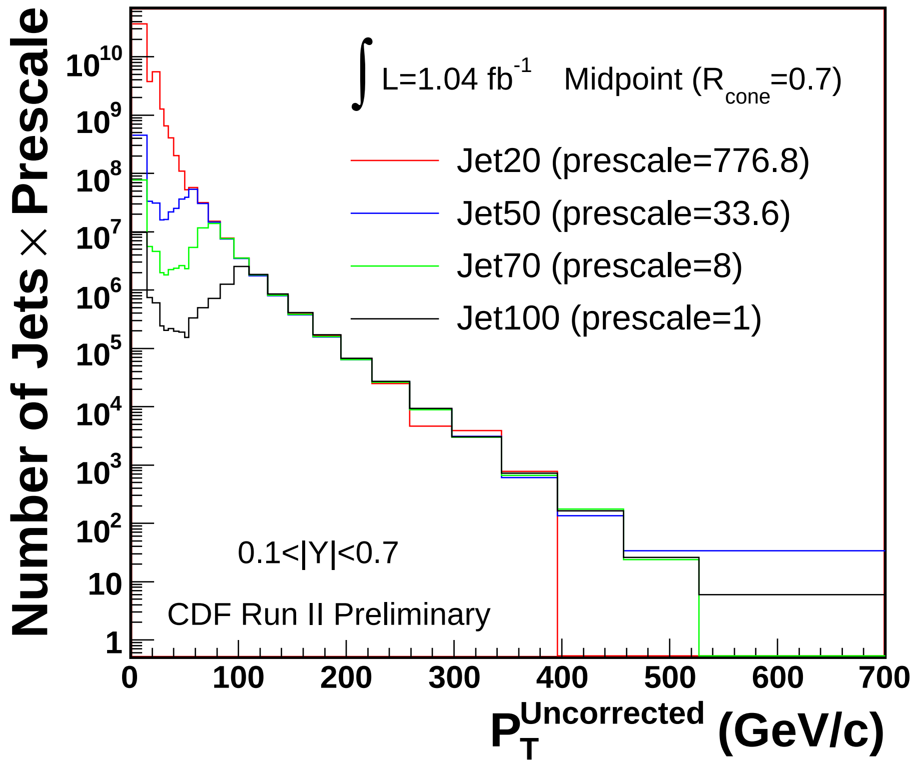
NOTE: CDF did not make a measurement in the forward region in Run I. Upgrades to the calorimeter and tracking system help make this possible in Run II.

Inclusive Jet Data Selection

- 4 jet triggers: jet20, jet50, jet70, and jet100.
- Use data set only when trigger efficiency is $>$ 0.995.

- Event selection
  - Missing E$_T$ significance cut ($\widetilde{\not{E}_T} = \not{E}_T / \sqrt{\sum E_T}$)
    - Cut is sample dependent (4,5,5,6).
    - Efficiency is $\sim$100% at low P_T and $\sim$ 90% at high P_T
  - $|Z_{vert}| \leq 60cm$ (95.8 % efficient).
  - At least 1 jet $|Y| < 2.1$. Split into 5 bins:
    - $0.0 < |Y| < 0.1$
    - $0.1 < |Y| < 0.7$
    - $0.7 < |Y| < 1.1$
    - $1.0 < |Y| < 1.6$
    - $1.6 < |Y| < 2.1$

Raw jet P_T distribution



We normalize this distribution to obtain the raw differential inclusive jet cross section:

$$\frac{d^2\sigma}{dP_T dY} = \frac{1}{\Delta Y} \frac{1}{\int \mathcal{L} dt} \frac{N_{jet}/\epsilon}{\Delta P_T}, \tag{1}$$

Before results can be compared with theoretical predictions the data must be corrected to remove detector effects.

Jet Energy Correction Strategy

∗ Based on Data:

- Correct for "pileup".

  ⟶ Correct for extra energy due to multiple proton-antiproton collisions in the event.

∗ Based on PYTHIA MC:

- Cal⟶Had: Correct for energy scale (absolute) and resolution (bin-by-bin).

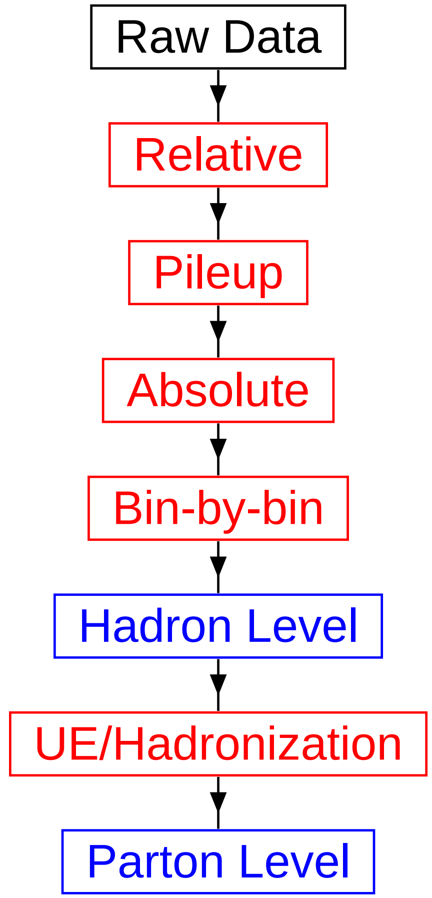
  ⟶ Average energy loss of jets due to non-compensating nature of the calorimeter.

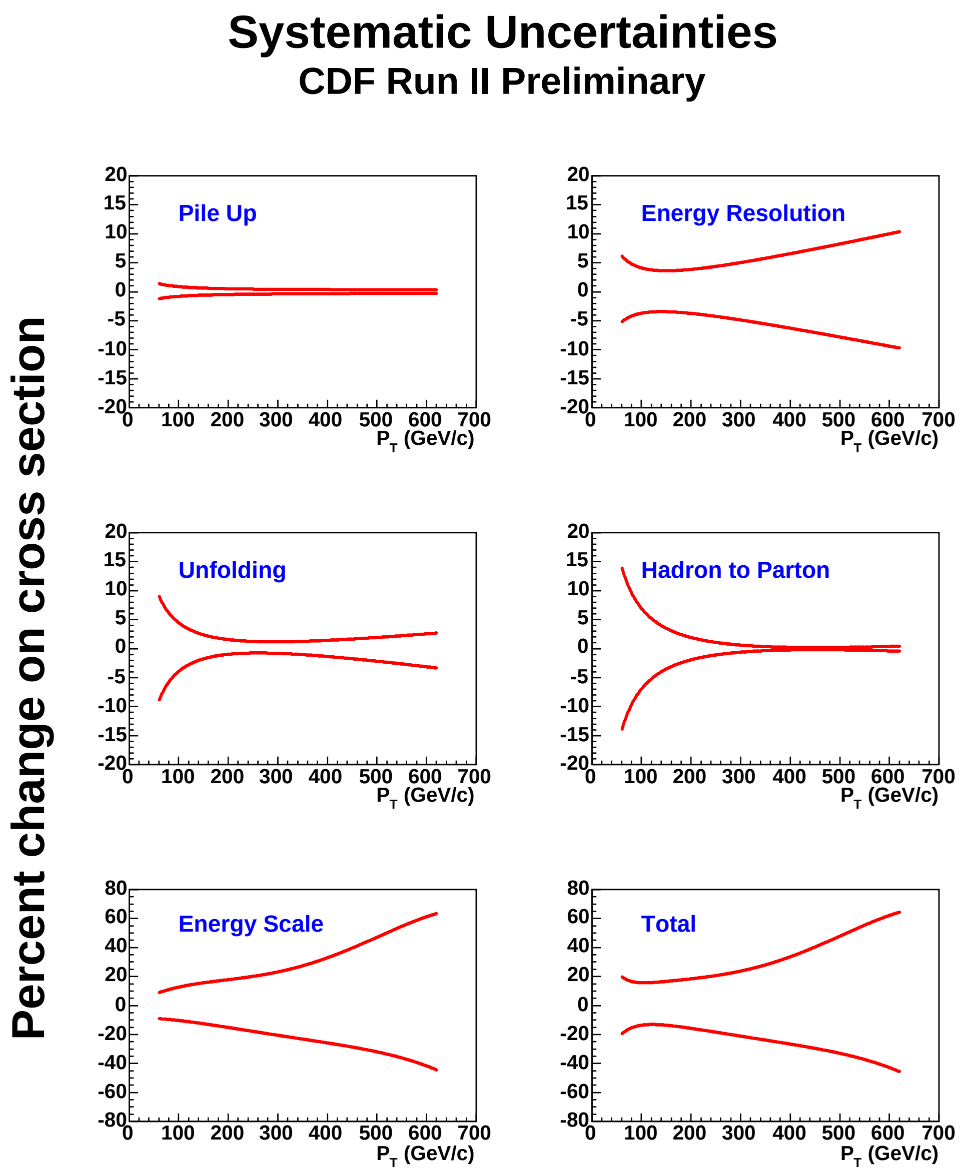
  ⟶ Smearing effect due to the jet energy resolution (10-20%).

- Had⟶Par: Correct for UE and Hadronization.

  ⟶ Extra energy from UE.

  ⟶ Energy loss 'out of cone' due to hadronization.

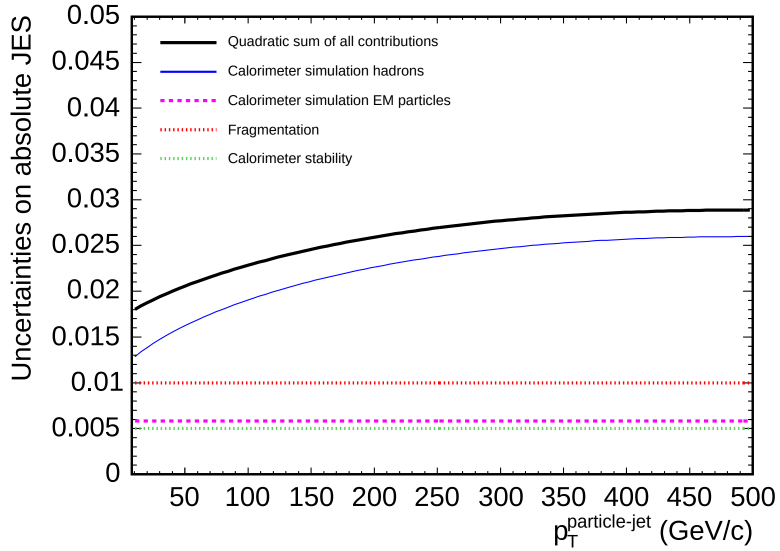


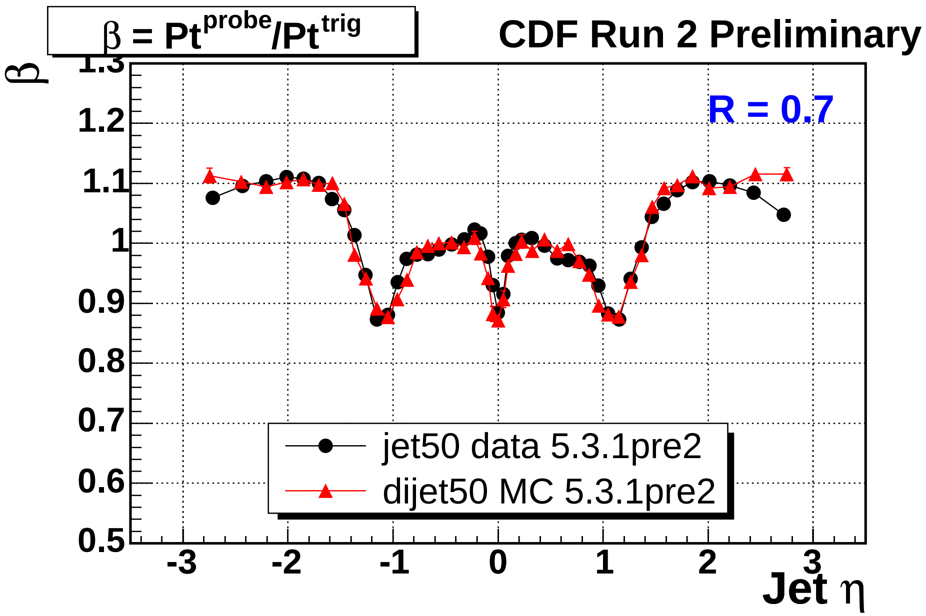


Systematic Uncertainties
CDF Run II Preliminary
Percent change on cross section
Pile Up
Energy Resolution
Unfolding
Hadron to Parton
Energy Scale
Total
P_T (GeV/c)

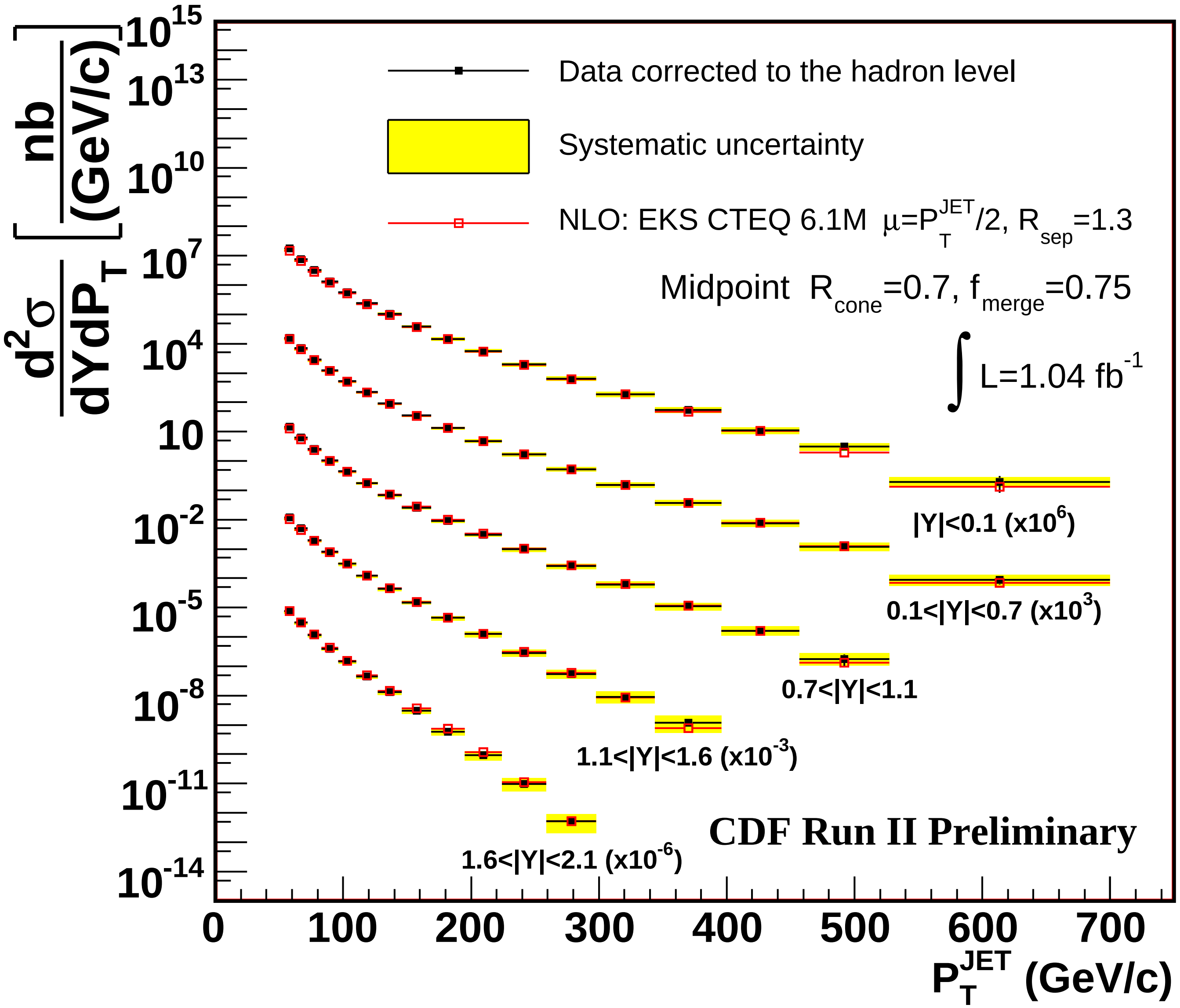
Jet Energy Scale at CDF

- In the central region, the jet energy scale (JES) is determined based on the detector simulation and jet fragmentation model.
- The detector simulation is tuned to reproduce the single particle response measured in-situ and in the test beam.
- Outside the central region, the jet energy scale is determined based on the relative differences to the central region observed in dijet Pt balance.
- Because of the steeply falling spectrum, a small uncertainty in the JES translates to a large uncertainty in the cross section measurement.

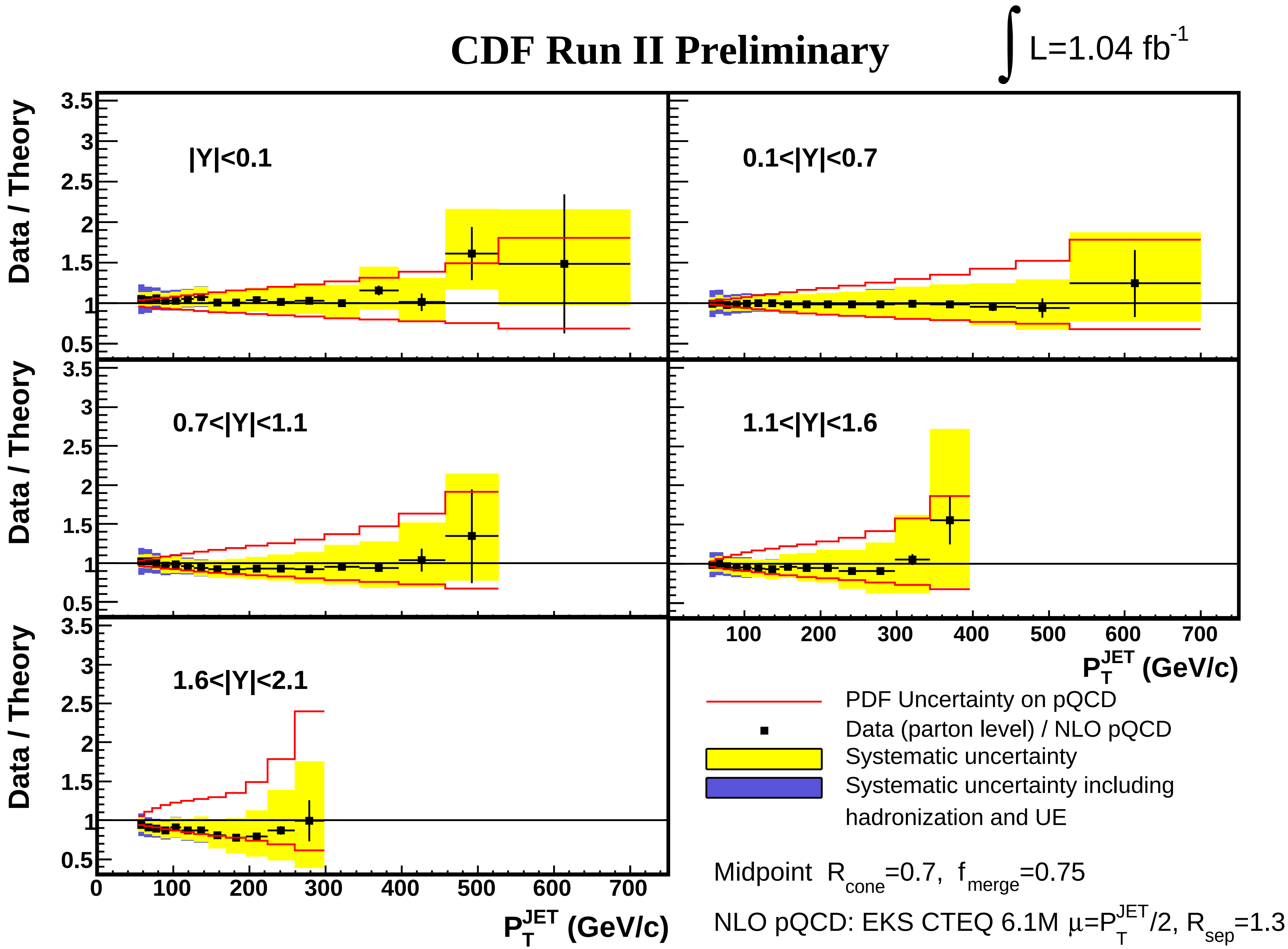




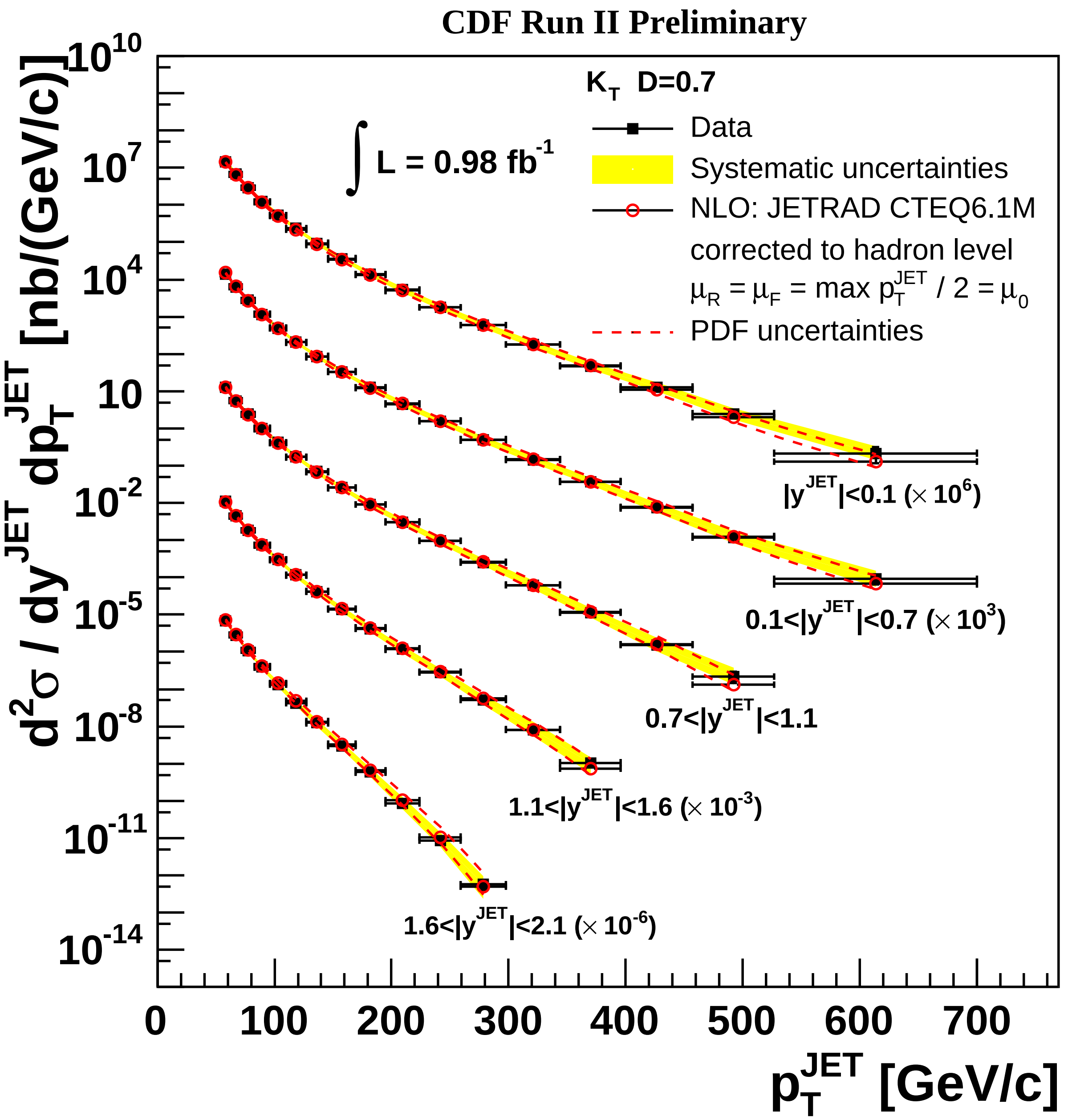
Midpoint Results: Cross Section Distributions



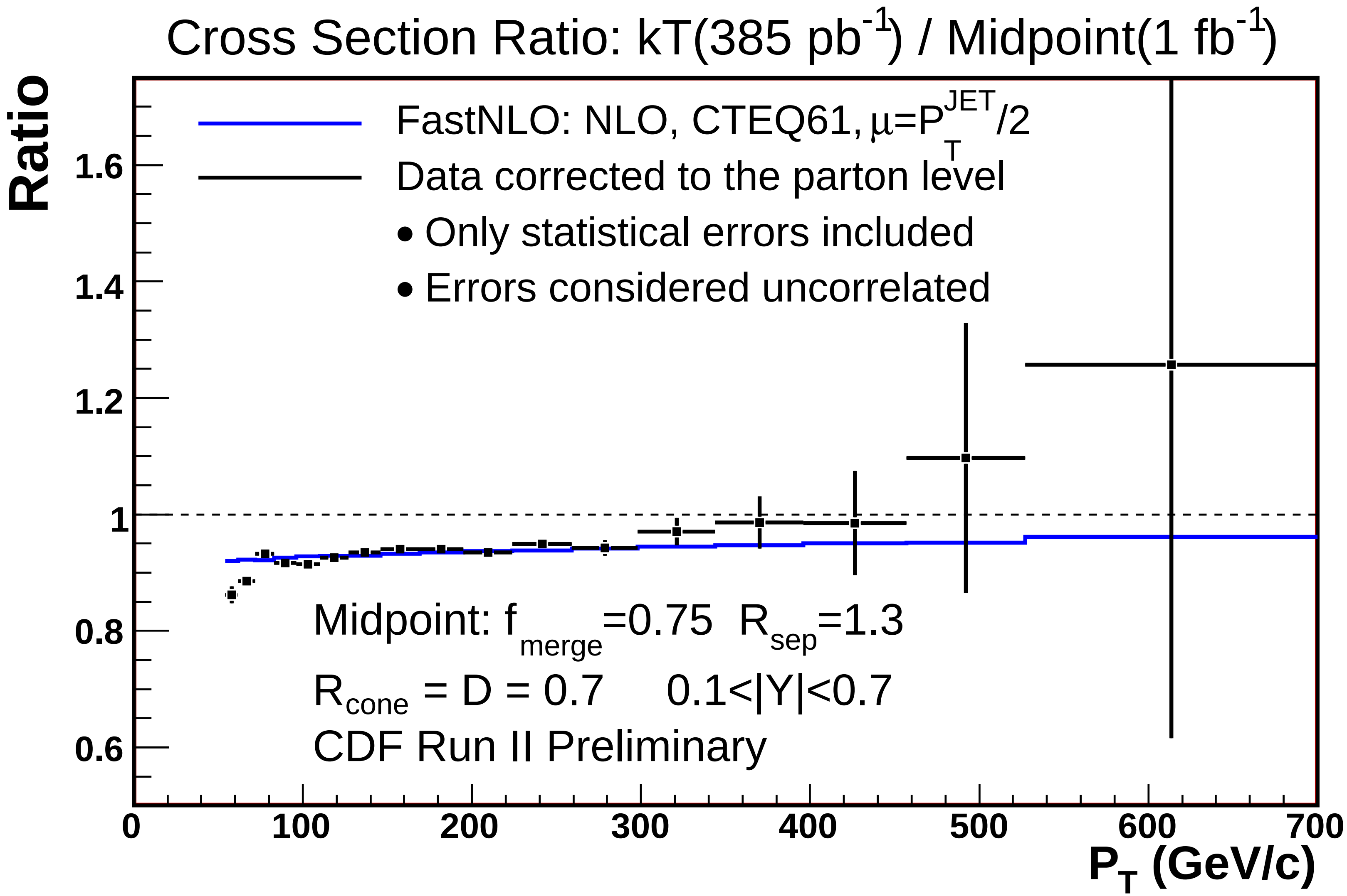
Midpoint Results: Ratio to NLO pQCD



K_T Results: Cross Section Distributions

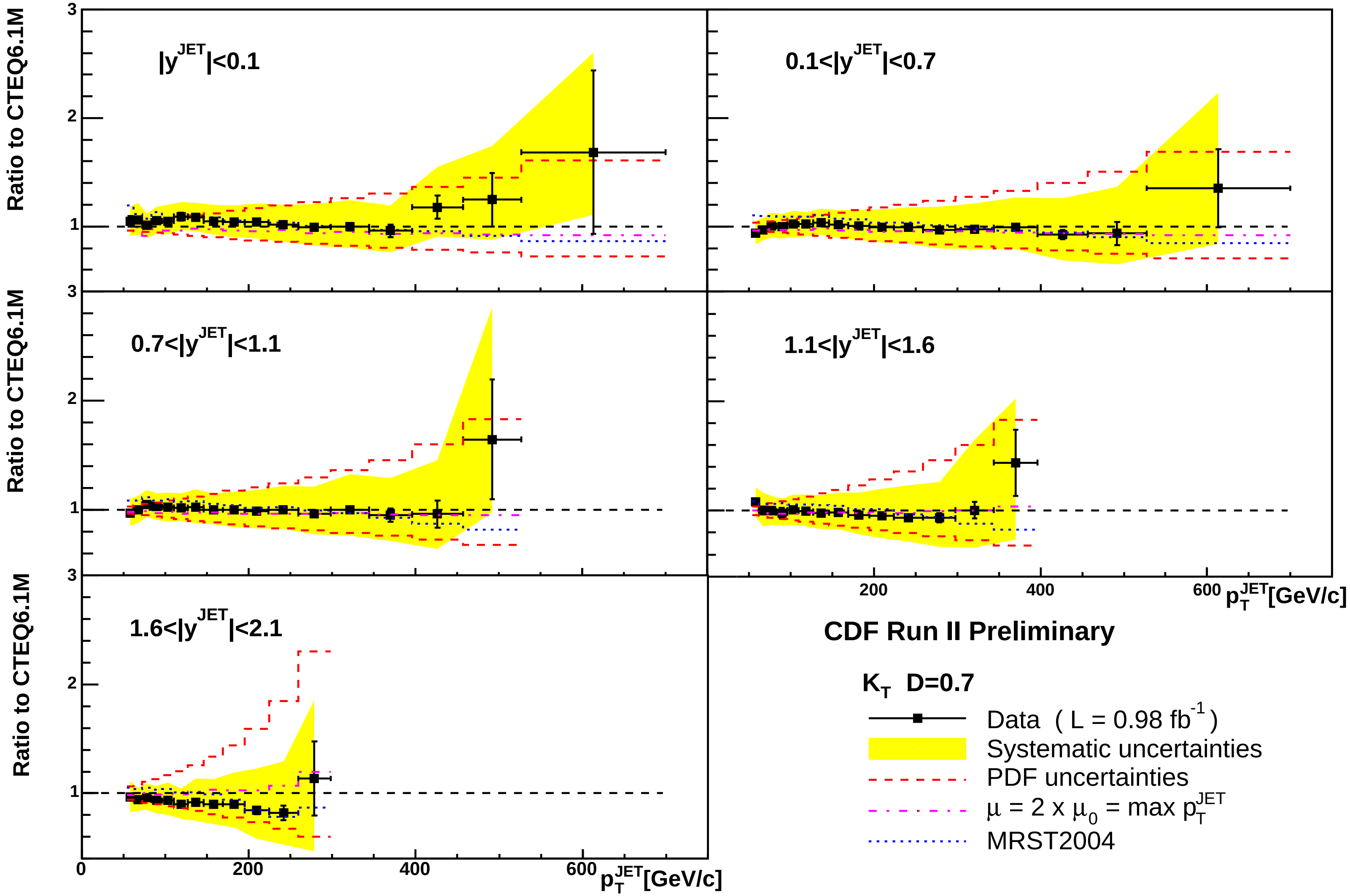


Algorithm comparison: K_T vs Midpoint



Nice agreement between cross section ratios predicted by NLO and data corrected to the parton level!

K_T Results: Ratio to NLO pQCD



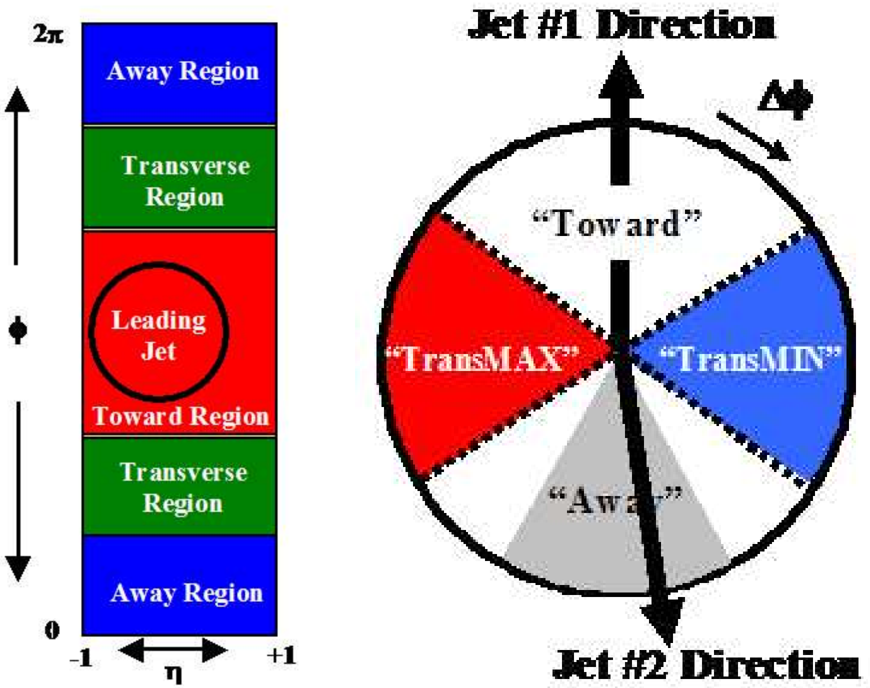
Summary and Conclusions

- Updated results on the inclusive jet cross section from CDF were presented:
  - Jets clustered by the Midpoint and K_T jet algorithms
  - Over $1fb^{-1}$ of data
  - Measurements extend to the forward region (up to $|Y| = 2.1$)
- Measured cross sections agree well with NLO pQCD predictions.
- Measurement is consistent between the $Midpoint$ and the K_T algorithm.
- K_T seems to work well in the hadron collider 'messy' environment.
- These results provide very important constraints on PDFs
  (especially the gluon densities at high x).

Other Research Efforts

- Underlying Event Studies with Rick Field
  - ∗ Tune JIMMY (add-on to HERWIG for MPI)
  - ∗ Tune PYTHIA 6.3 (New UE model)
- SUSY MC studies with Konstantin Matchev
  - ∗ Slepton mass measurements at the LHC
  - ∗ SUPERSIM
- PDF Tools
  - ∗ LHAPDF/LHAGLUE
  - ∗ LHAPDF at CDF
- Other CDF service projects
  - ∗ Relative jet energy corrections
  - ∗ QCD Stntuple management
  - ∗ UF grid site part of CDF NamCAF

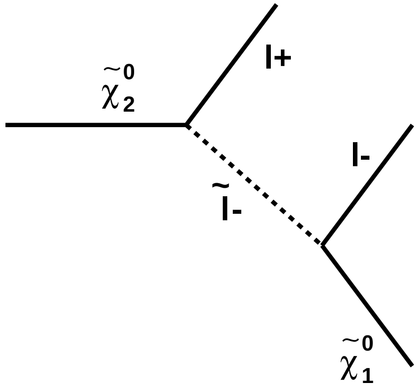
Underlying Event Studies at CDF

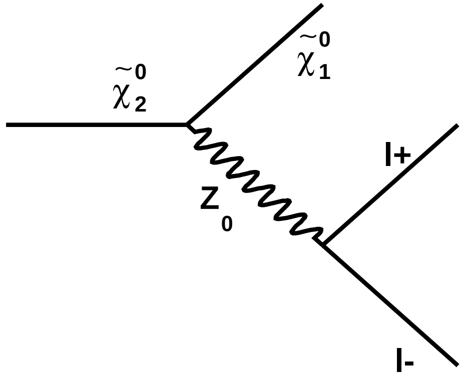


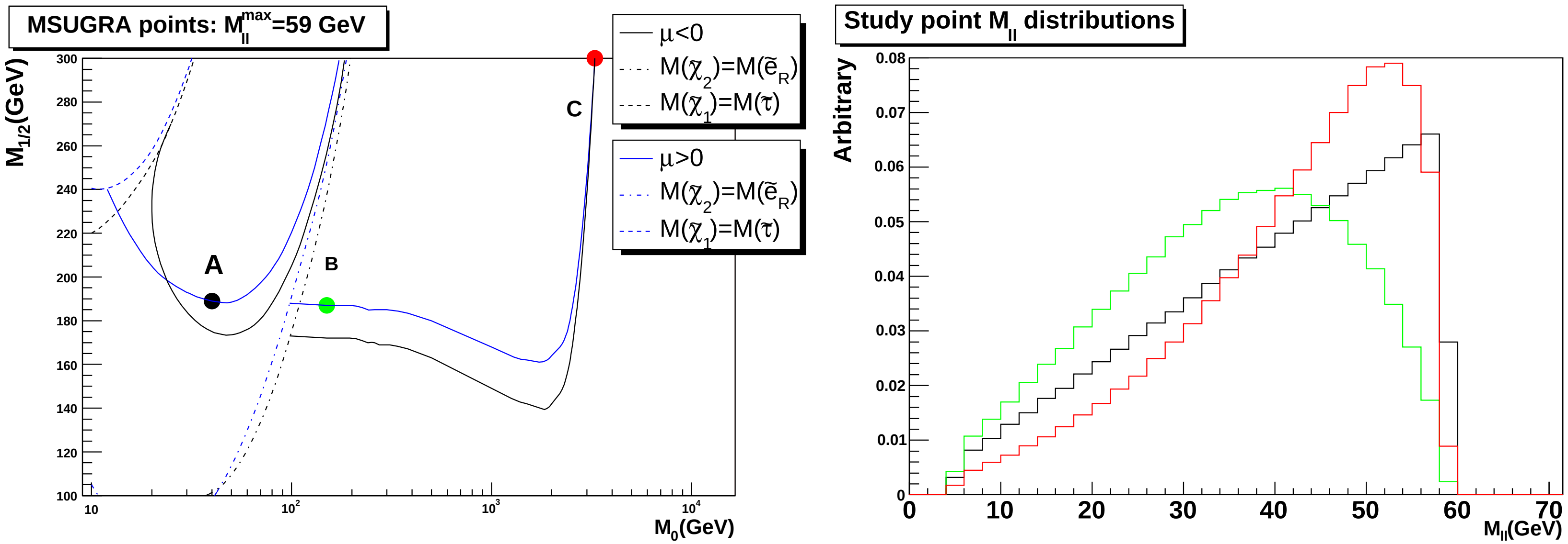
Using the *leading jet* and *back-to-back* topologies we use many observables to study the UE event. The *transverse* regions (*TransMAX* and *TransMIN*) are particularly sensitive to the UE observables.

We are working towards publishing the UE study with over $1\ fb^{-1}$ of CDF Run II data.

The shape of the invariant mass distributions of opposite-sign lepton pairs from SUSY cascade decays changes when the mass of the intermediate slepton is varied..







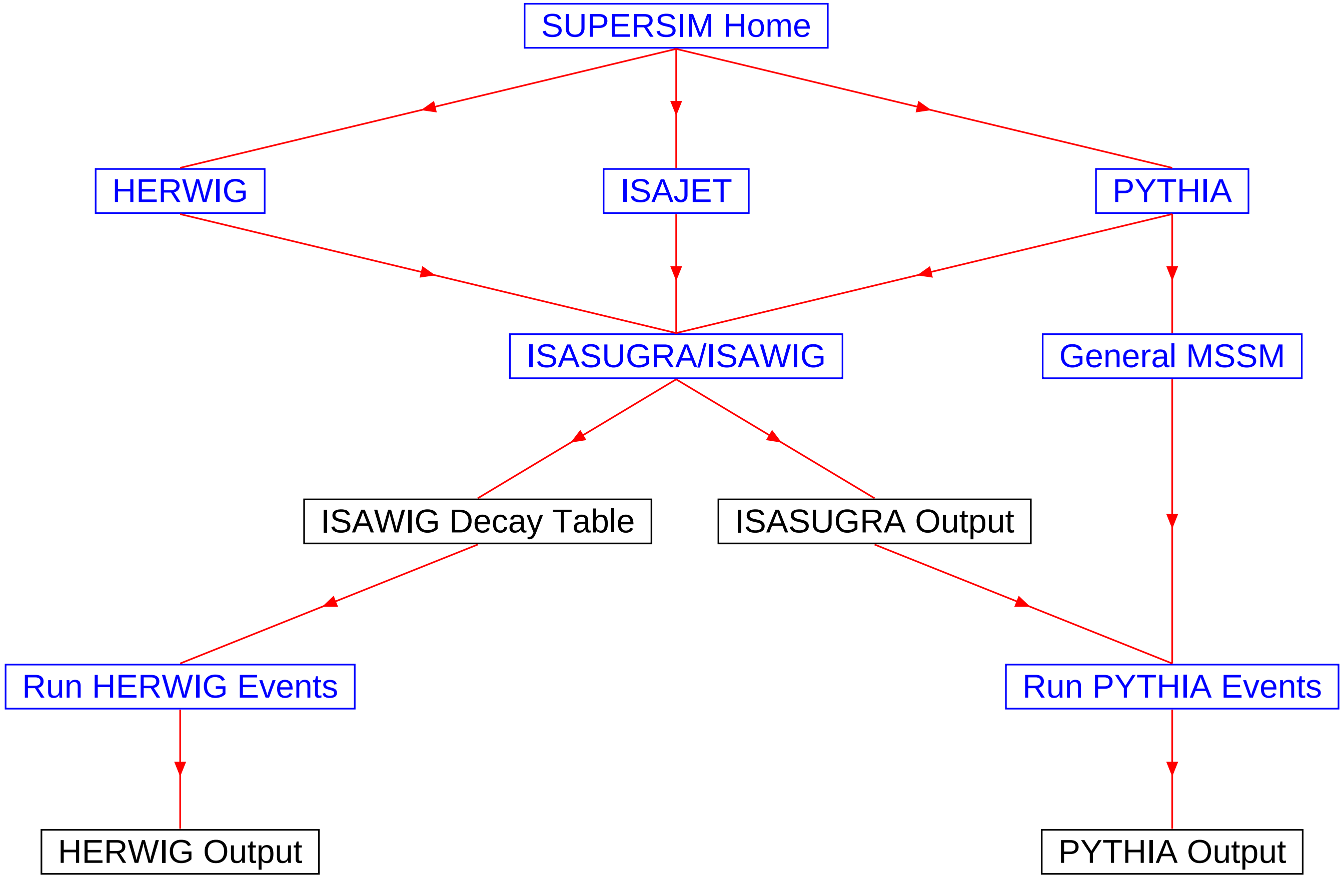
SUPERSIM

- http://www.phys.ufl.edu/supersim/

  $\longrightarrow$ Try it out!

- I lead a REU summer student on this project

- Python CGI web interface to SUSY tools provide:
  - SUSY mass spectra and branching fractions via ISASUGRA
  - SUSY cross sections from PYTHIA or HERWIG



NOTE:The black boxes represent steps with useful output

PDF Tools

LHAPDF code development

- Co-author of LHAGLUE (Wrote HERWIG interface)

  (LHAGLUE is a PDFlib-like interface for MC generators to the LHAPDF library)

- Co-author of a wrapper for using LHAPDF (V5) with a C++ program

  (This also works with root!)

- Help test and validate new releases

- Studies on techniques for calculating PDF uncertainties

- Helped incorporate LHAPDF into cdfsoft and serve as LHAPDF librarian

Service activities

- Relative Jet energy corrections at CDF
  - Tested and maintained relative corrections for new data
  - Used stability of relative correction to validate JES
- Stntuples at CDF
  - Generated and managed Stntuples for QCD group
  - Maintained web-page for easy Stntuple access by CDF collaboration
- Florida grid cluster added to CDF NamCAF

www.phys.ufl.edu/∼ group

Work Links

- Recent Work
- CDF Page

Career Information

- Curriculum Vitae: ps, pdf
- Research Experience: ps, pdf
- Publication List: ps, pdf

General Links

- SPIRES (jobs)
- GOOGLE, Hotmail, BOFA
- Old Home Page

Robert Craig Group

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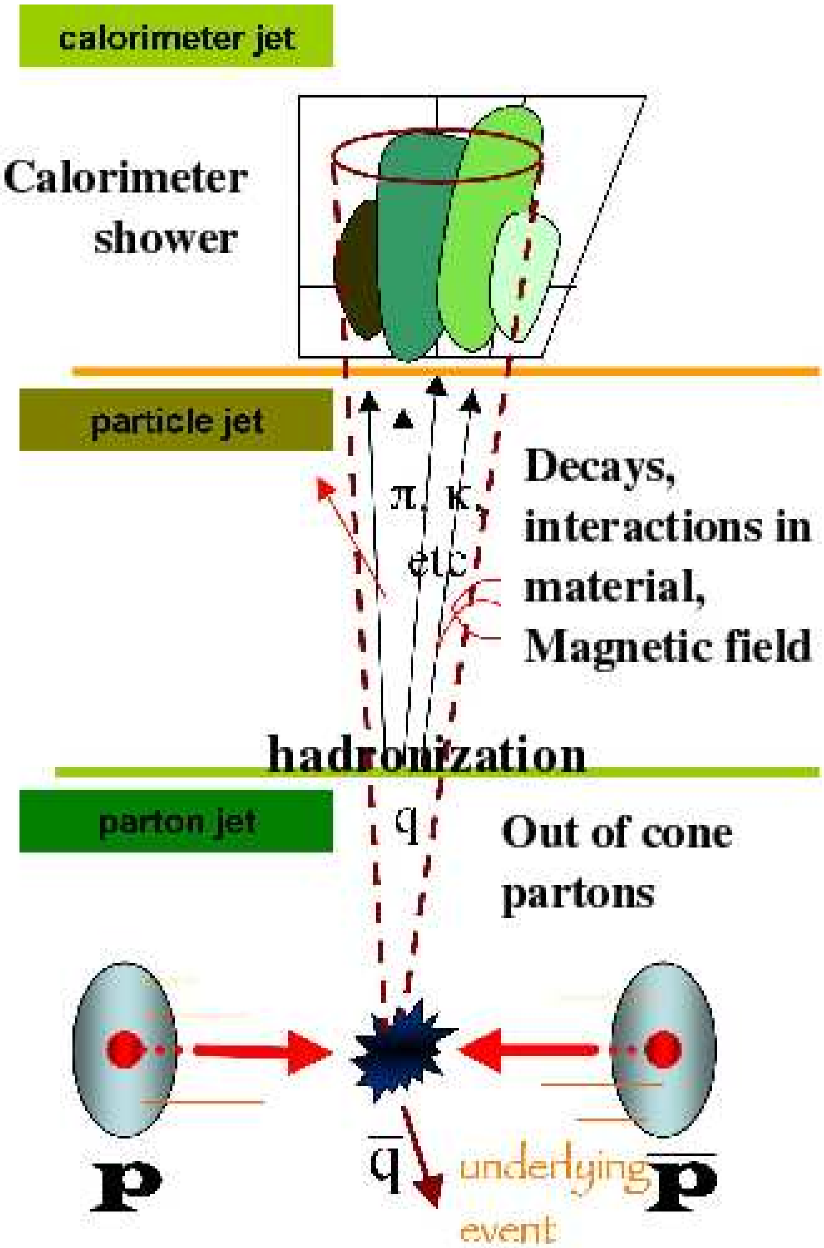
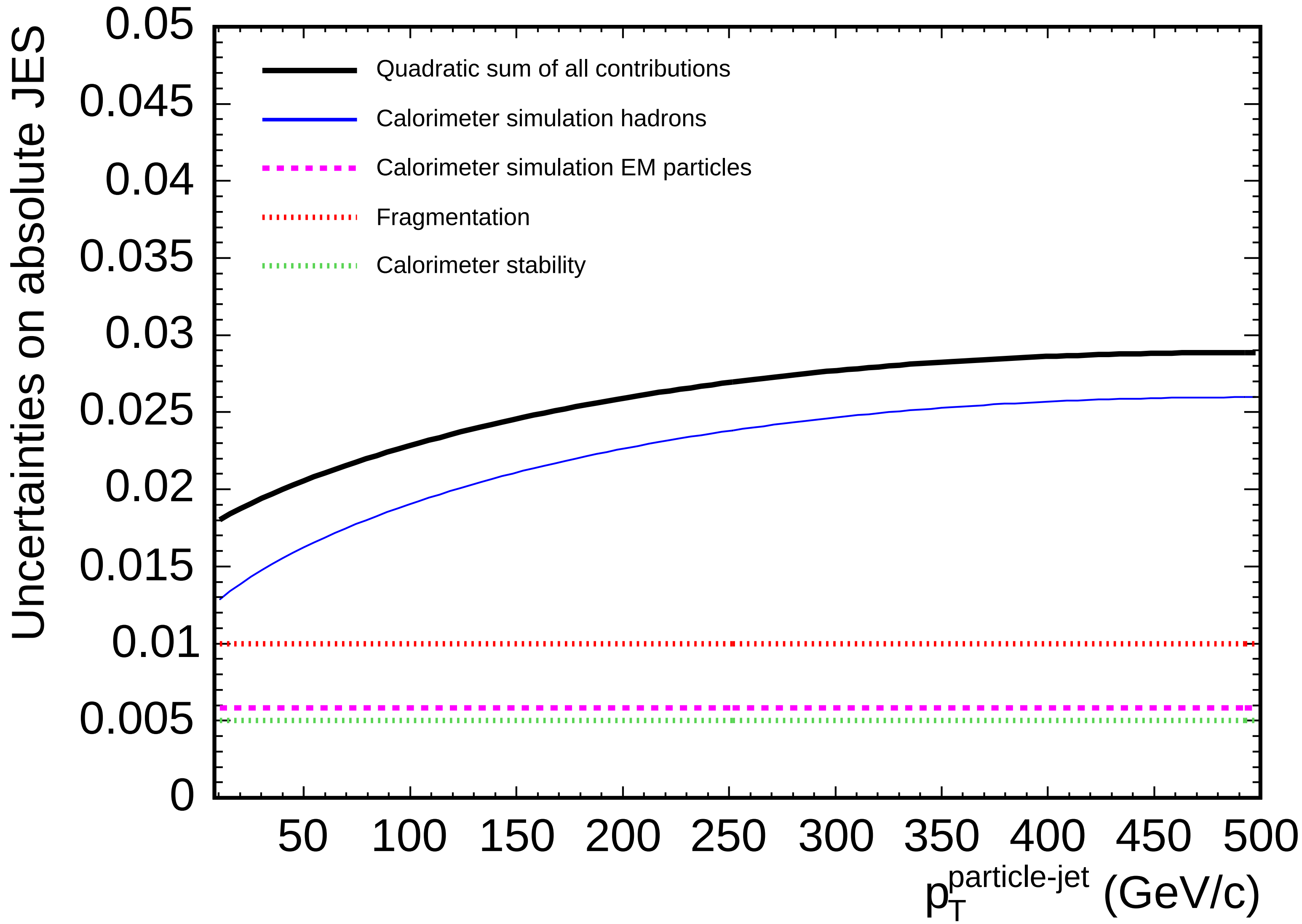
More information about all of these projects as well as my talks and publications can be found on my web page.

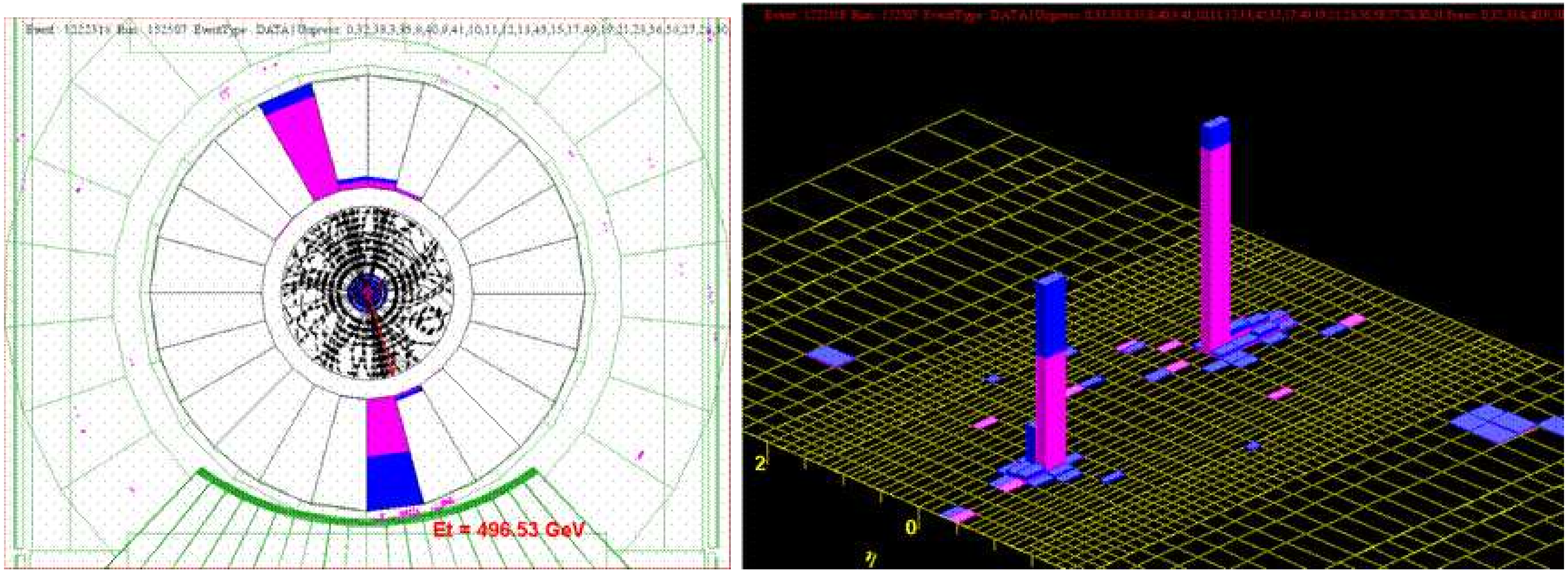
BACKUP

Jet Production at the Tevatron



JES Uncertainty

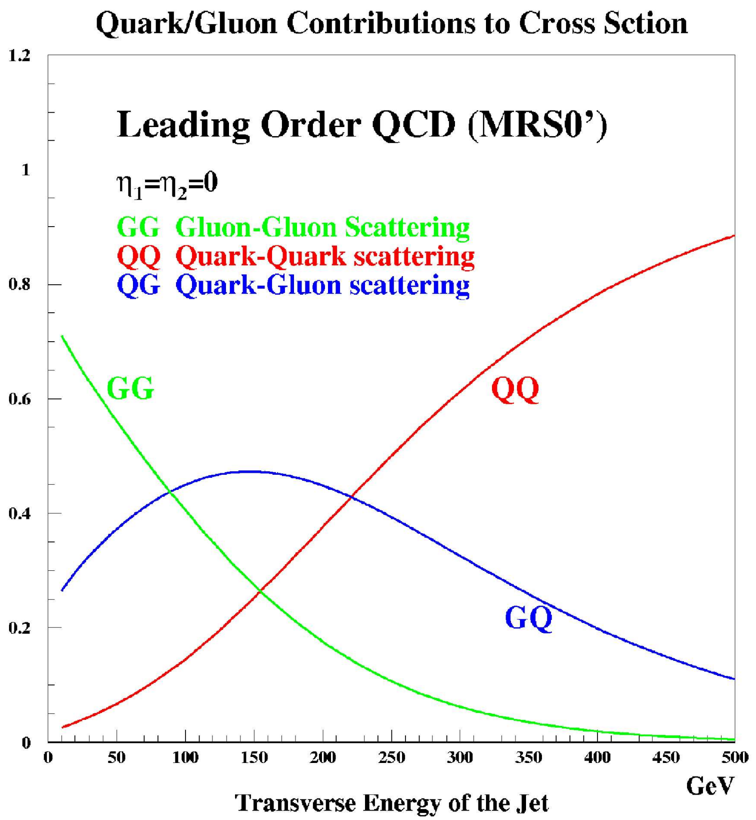


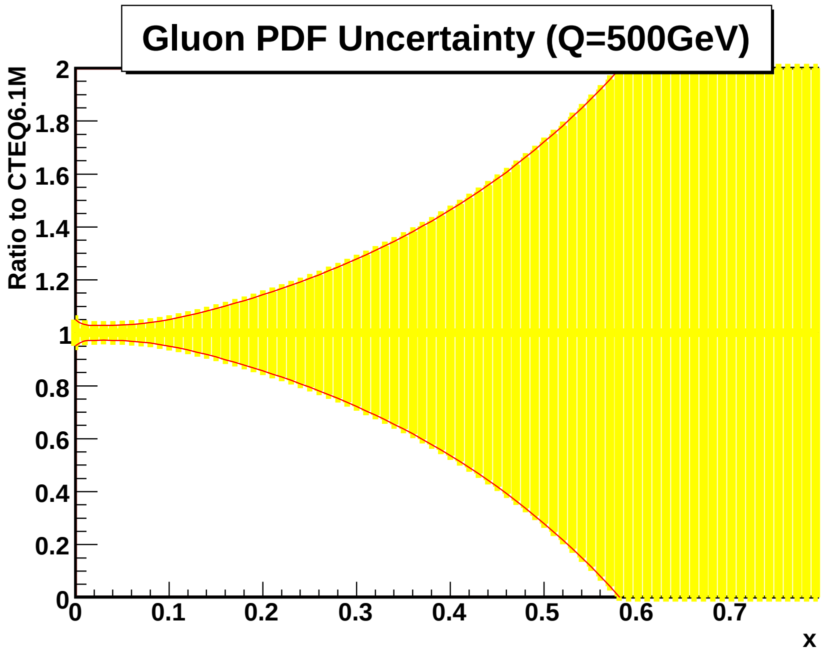


Highest energy dijet event measured so far at CDF.

$$(P_T^{Raw} \sim 580 GeV)$$

Gluon contributions at high x



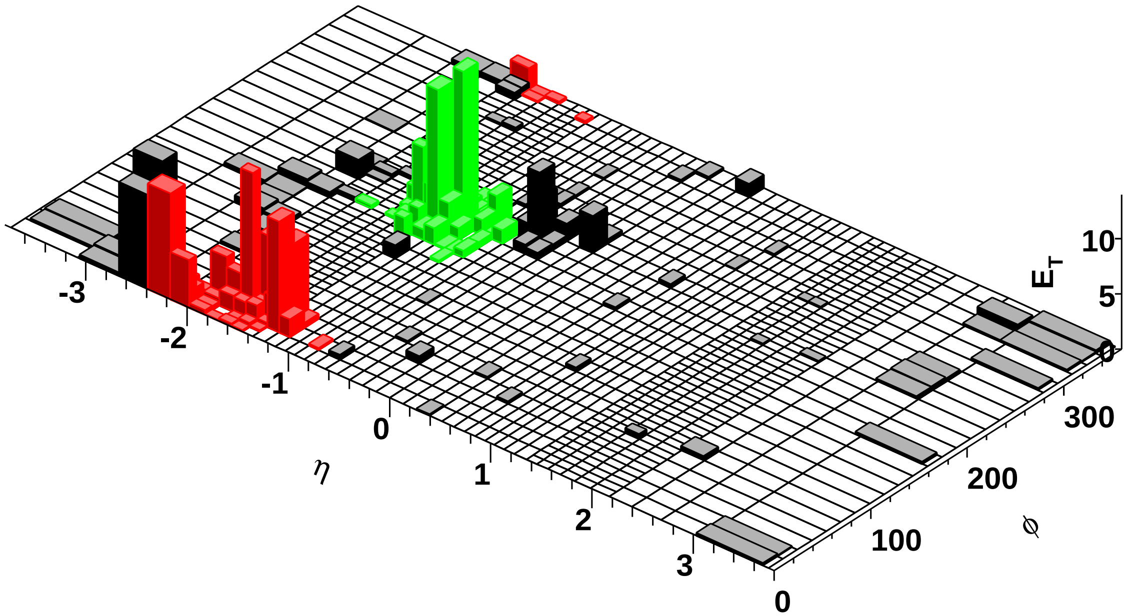


MC Checks and Corrections

Before the MC and detector simulation can be used to correct the data it must be checked that CDF detector simulation is accurately describing the real CDF detector.

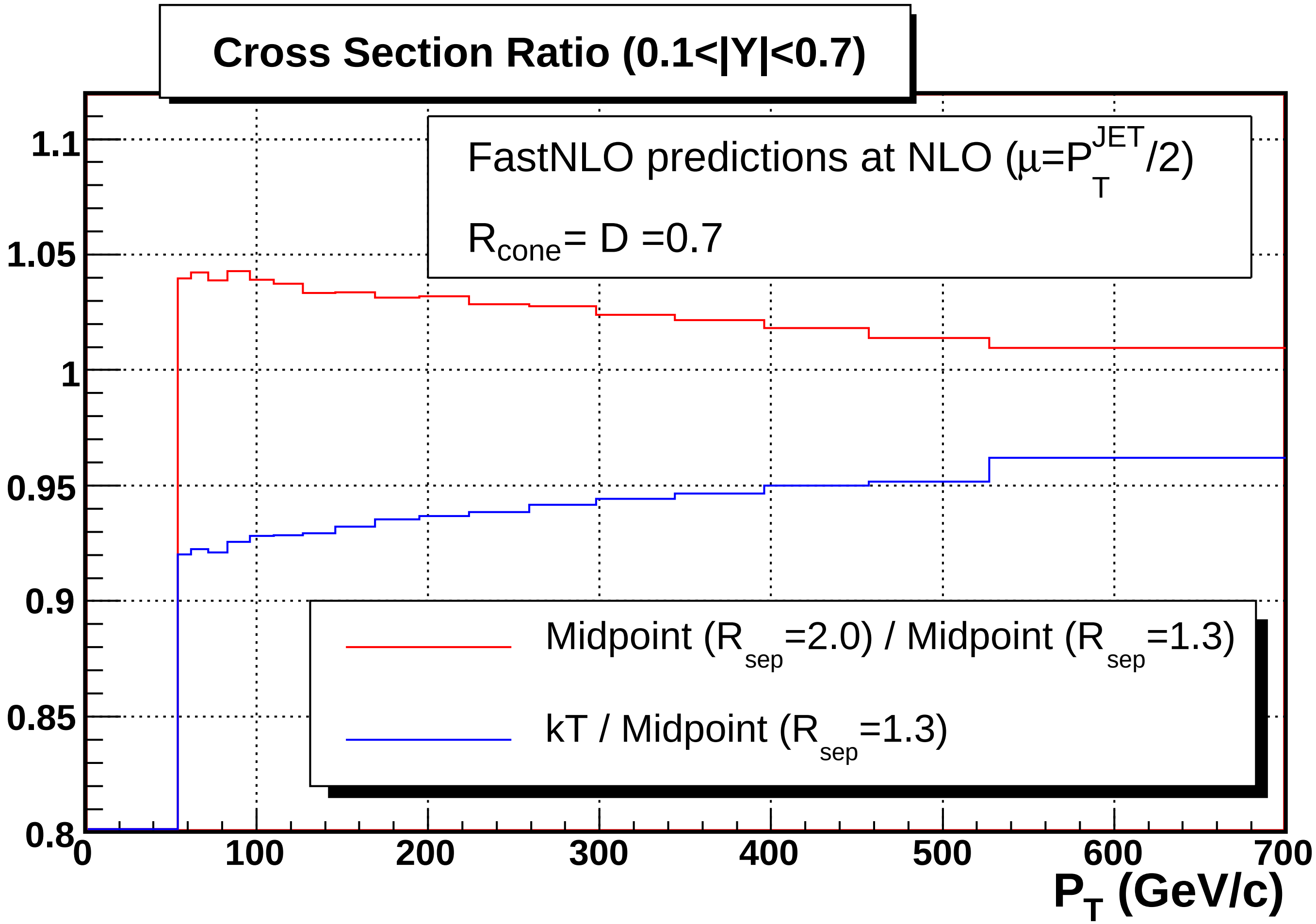
- Bisector Method: Used to compare jet resolution in the CDF simulation and the data.
  - Central region agrees well between data and MC
  - $0.7 < |Y| < 1.1$ and $1.6 < |Y| < 2.1$ under smear jet energy
  - $|Y| < 0.1$ and $1.1 < |Y| < 1.6$ over smear jet energy
  - Hadron level study is used to derive bin corrections for the resolution.
- Dijet Balance: Used to compare central/non-central relative calorimeter response in the CDF simulation and the data.
  - Results are used to correct MC.
  - There is a large systematic uncertainty from this correction at high P_T in the high rapidity regions.
- PYTHIA re-weighting : Force the shape of PYTHIA cross section to agree with data so that unfolding corrections are not biased.
  - Difference in shape may be due to PDF
  - Weight events $\longrightarrow$ modified unfolding factors.

The Search Cone.

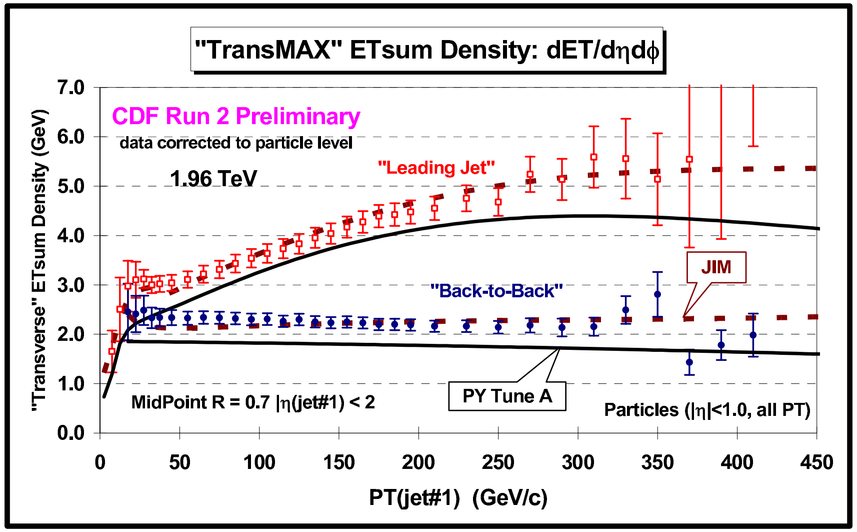


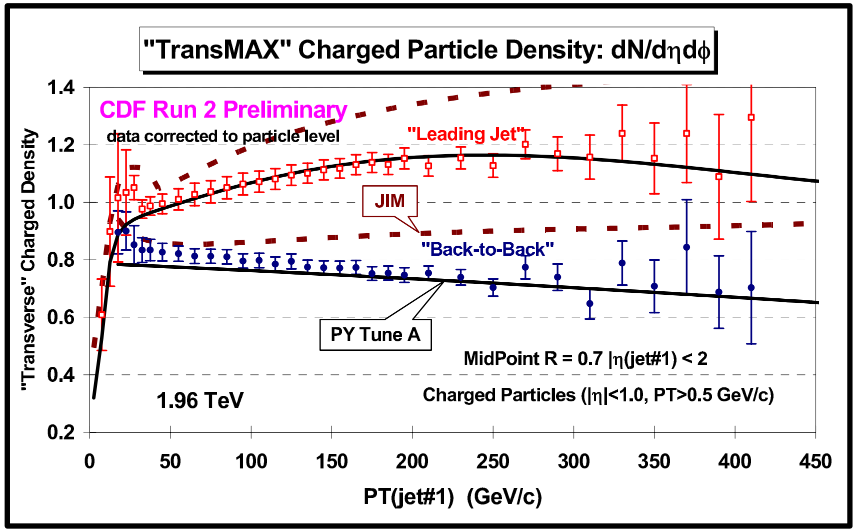
- CDF observed “dark” towers in some events.
- To improve the match between parton, hadron, and detector level jets the search cone was added to minimize this effect. Search for stable cone with $R_{cone} = \frac{R}{2}$ then expand to $R_{cone} = R$.
- Results in a 5% increase of the jet cross section.

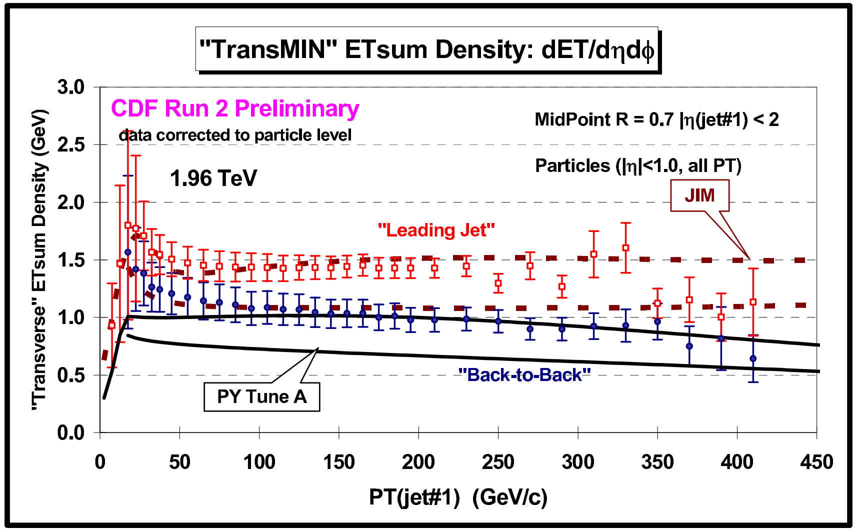
R_{sep} quantitative effect

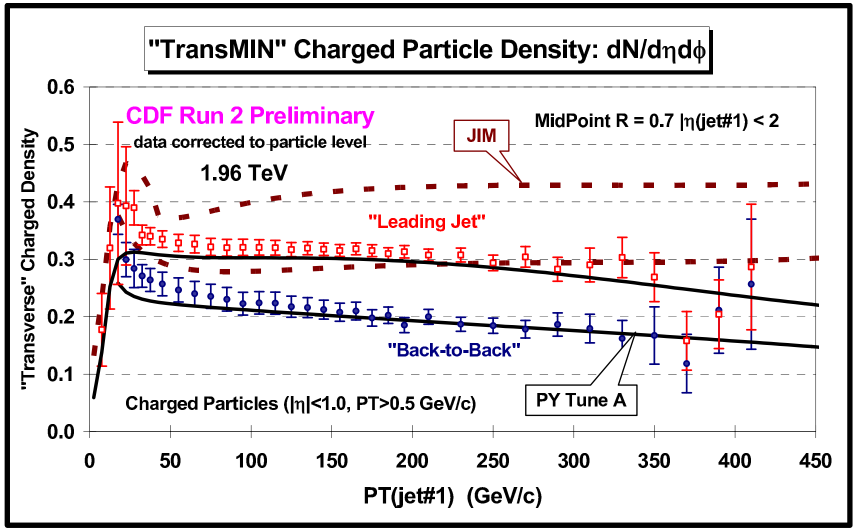


Example: UE Studies at CDF



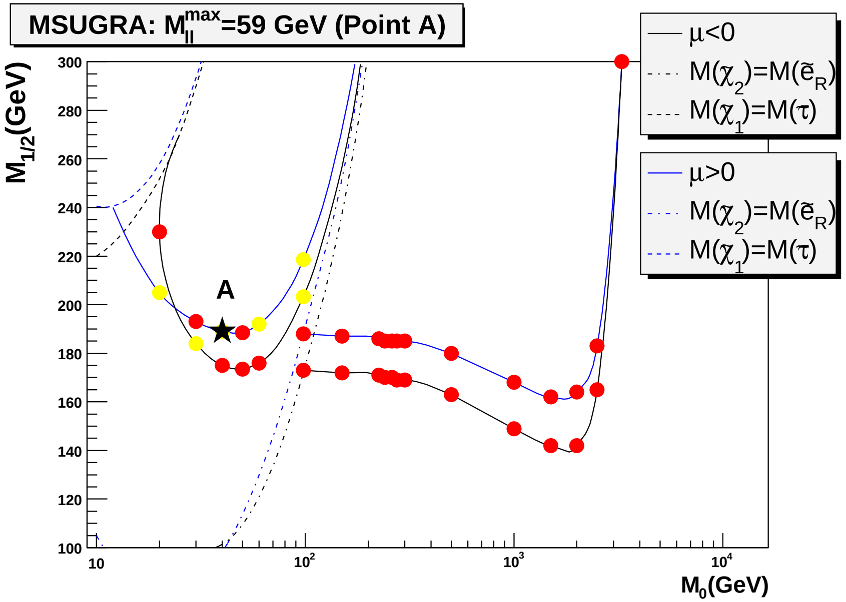


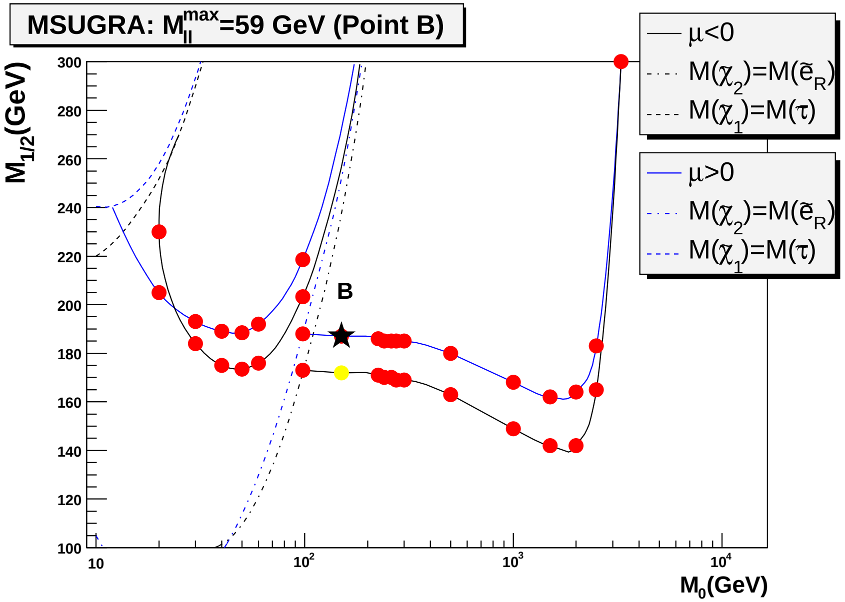


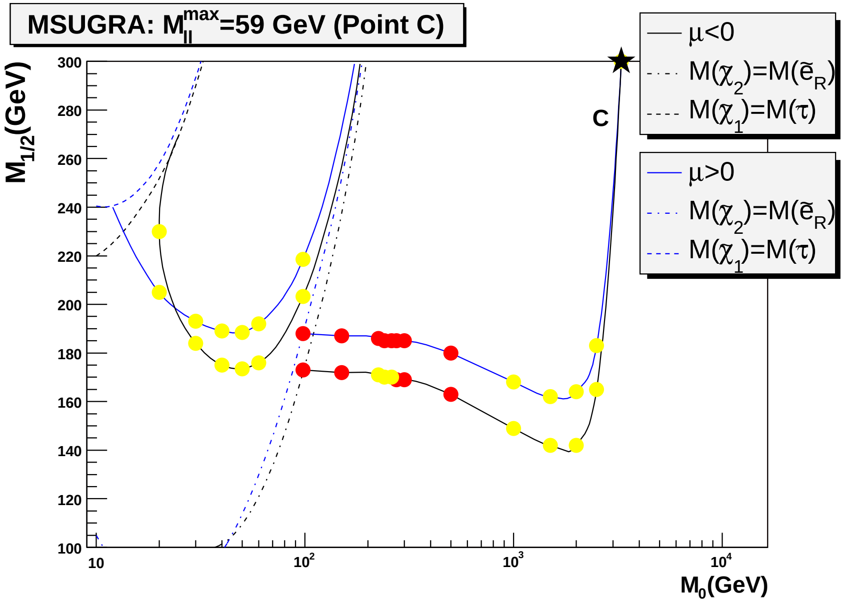


Slepton Mass Measurements at the LHC

Results of 'template' based analysis using the KS test..







Kolmogorov-Smirnov Test

The shapes of these M_{ll} distributions are quite different even to the naked eye. However, the K-S test may be used to quantify these differences in a systematic way.

$\longrightarrow$ The K-S test looks at the maximum difference between the cumulative distribution functions.

$\longrightarrow$ A null hypothesis is made that the two samples come from the same underlying distributions.

$\longrightarrow$ The K-S test then calculates the confidence level with which the null hypothesis can be falsified.